PENCEL Pressuremeter Test Evaluation for Developing P-Y Curves for Driven Piles

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Abstract*—The study goal was to demonstrate that PENCEL pressuremeter (PPMT) test would generate reliable engineering parameter to allow engineers to more precisely carry out the standardized tests, and to produce the p-y curves for analysis and design of laterally loaded piles. The PENCEL was pushed to the desired test depth using the Cone Penetrometer equipment. Based on the results of a comprehensive testing program the evaluation indicates the testing procedure is acceptable. A recommended interpretation and procedure are presented. An evaluation of the proposed methods is presented using data from a number of in-situ PPMT tests conducted in Cape Canaveral site. From PPMT data, which were reduced to graphs of pressure versus volume and pressure versus relative change in probe radius, soil parameters including the lift-off pressure, the initial elastic moduli, the reload moduli, and the limit pressure of the soils were determined. The two latter parameters were utilized to establish the p-y curves via the conversion of the PPMT stress to force per unit length and the PPMT strain to obtain displacement.The PPMT soil parameters show good agreement with published values. Dilatometer (DMT) tests were conducted for comparisons with PPMT data. Correlations were developed between the PPMT and DMT results, which show consistency in soil parameters values. Comparison between PPMT and DMT p-y curves were performed based on the slope of the initial portion of the curve, the curves shape, and the ultimate soil resistance. The initial slope shows a good agreement for this comparison. The expected PPMT and DMT deflections within the elastic range are identical, while the expected DMT and PPMT ultimate loads are not similar. It is possible to install the PPMT in a manner which models the disturbance caused during pile installation and predict the analysis of the laterally loaded soil resistance.

***Index Terms*—PENCEL Pressuremeter test, piles, lateral loads, p-y curves, Dilatometer, pressure, moduli. clays, sands.**

I. Introduction

The pressuremeter (PMT) Technology has progressed significantly since, with advances in material science and suggestions for modification based on a variety of research in various applications. The PMT consists of a cylindrical probe containing an inflatable balloon, which is lowered into the soil to produce in situ stress-strain responses, was originally developed by Ménard (1956) and modified by Briaud and Shields (1979). Most PMT testing is conducted once the drillers prepare the prebored test hole and the probe is lowered to the desired position. These larger diameter pressuremeters are naturally more cumbersome to work with than the PPMT. A variety of PMT models are currently available, although they are typically based on two widths, the standard 3-inch diameter probes lowered into boreholes and the specialty 1.35-inch diameter PENCEL probes pushed when attached to cone rods (Briaud, 1992). The PPMT is shown in Figure 1 with the probe connected to the unit through tubing and the pressure and volume gauges for recording data by hand (Roctest, 2005). Anderson and Townsend (1999) saw advantages in connecting the PPMT probe to Cone Penetrometer (CPT) rods and either pushing the cone with the PPMT attached or pushing the PPMT separately to perform PPMT tests. Finally, this device was further advanced by 1) developing a standardized testing procedure as recommended by Cosentino et al (2006) and 2) integrating digital technology with data acquisition software generating significant time savings and improved precision as a fully reduced stress-strain curve is created during testing (Cosentino et al, 2006). PPMT equipment has been successfully used throughout Florida in clays and sands (Anderson and Townsend 1999), (Cosentino et al, 2006).

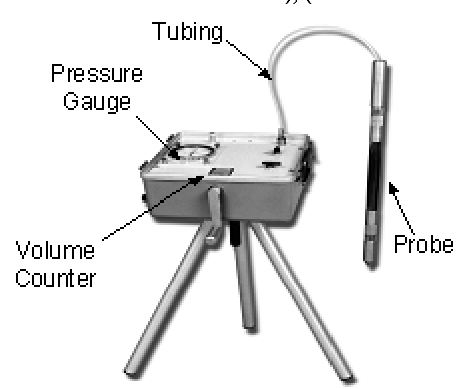

Figure 1. PENCEL Pressuremeter (After Roctest 2005).

A. Process

A series of calibrations are conducted based on the system saturation requirement; one that accounts for the intrinsic membrane resistance, and a second, for the tubing expansion and the membrane thinning during pressurization. Furthermore, a hydraulic correction is applied to the pressures,

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for the reason that the test is conducted at a recognized depth below the pressure gauge.The PPMT probe is hydraulically pushed with the equipment in the CPT rig to the desired test depth and the 10-to15-minutes standardized test recommended by Cosentino et al (2006) is performed.

A strain-controlled process is utilized during this standard test, concerning operators to inject equal 5 cm^3 volumes of water into the probe, wait 30 seconds and then record the corresponding pressures to allow the device to be stabilized at that depth. The probe volume is incrementally increased an additional 90 cm^3. The operators also determine the extent of the linear stress–strain response range before performing one unload–reload cycle on the soil. This determination needs several complex steps; therefore, Cosentino et al (2006) incorporated digital equipment and data acquisition software, called APMT for Automated Pressuremeter that simplified the method, yielding more accurate data while easing operator needs .

B. PPMT Curves Interpretation

Several adjustments must be made to the raw curve, based on readings taken from PPMT test, in order to plot a reduced curve as shown in Figure 2. This figure contains both the membrane calibration curve and the volume calibration line, which are subtracted from the raw data to produce a reduced curve.

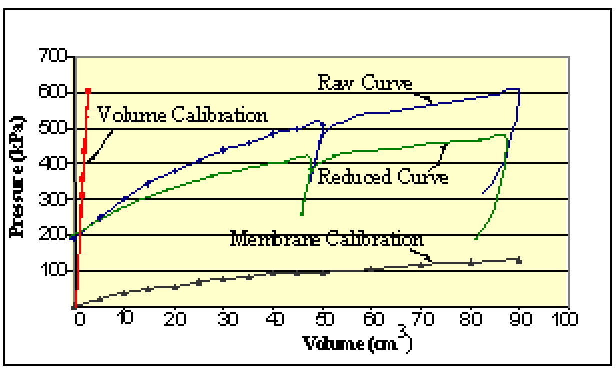

Figure 2. Raw and reduced curves with calibration applied (Cosentino et al 2006).

In order to determine the critical engineering parameters, Figure 3 shows four critical portions of the reduced curve that are used for estimating: 1) The initial pressure (p_0) from repositioning phase, 2) An initial elastic modulus (E_0) from the elastic phase, 3) An elastic reload modulus (E_r) from the elastic reload phase, and 4) The limit pressure (p_L) from plastic phase.

Elastic moduli are determined from the following equation (Baguelin et al, 1978):

$$E = 2(1+\nu)\frac{\Delta P}{\Delta V}V_m \qquad (1)$$

where, E = Young's modulus ,
ΔP = change in stress ,
ΔV = change in volume related to ΔP,
V_m = average volume,
ν = Poisson's Ratio.

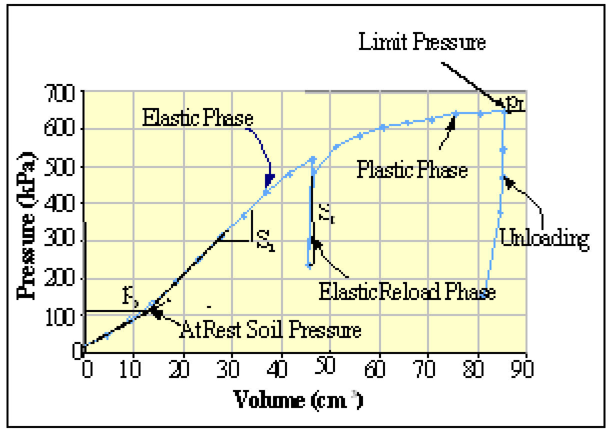

Figure 3. Engineering parameters obtained from reduced data.

II. Field Testing Program

An inclusive field-testing program was performed at Puerto Del Rio Complex in Cape Canaveral, Florida, enabling soils to be evaluated. In addition to PPMT tests, Cone Penetrometer (CPT) and dilatometer (DMT) tests were conducted. All testing was conducted using the Florida Department of Transportation (FDOT) State Materials Office CPT rig and personnel. Over 100 PPMT and DMT tests were conducted at this site.

The Cape Canaveral site consists of interbedded sands and clays. There were two clay layers that were the focus of the research. An upper clay layer approximately 2 m (6 feet) thick was normally consolidated and had an average density of 14.4 kN/m^3 (92 pcf) and a lower normally consolidated layer from the 10 to 15 m (30 to 50 feet) depth with an average density of 15.3 kN/m^3 (97 pcf).

The process used during PPMT testing was the recommended FDOT standard (Cosentino et al, 2006). During the strain-controlled test, operators monitored stress versus volume data to determine the extent of the elastic range. Once this range was complete, unloading to one-half the existing pressure then reloading to the original pressure was performed followed by the remainder of the strain-controlled test (Figure 3). The American Society for Testing and Materials (ASTM) procedure D 6635 was followed for all DMT testing, while CPT tests were conducted in accordance with ASTM D 5778. For evaluating DMT data, Marchetti (1980) presented equations involving several preliminary calculations to determine a Young's modulus of elasticity (E). After obtaining the two basic test parameters; the lift-off pressure (A) or the pressure on the DMT membrane once it is pushed to the preferred depth and the maximum pressure at 1.1 mm of movement (B), a corrected contact stress is found using the equation:

$$p_0 = 1.05(A - Z_M + \Delta A) - 0.05(B - Z_M - \Delta B) \qquad (2)$$

where Z_M is the gauge pressure when vented to the atmosphere, while ΔA and ΔB are calibration pressures subtracted from the lift-off and maximum readings. A corrected expansion stress is then found using the equation:

$$p_1 = B - Z_M - \Delta B \qquad (3)$$

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The DMT modulus, not Young's Modulus, is then found from the equation:

$$E_D = 34.7(p_1 - p_0) \qquad (4)$$

This DMT modulus can be converted to a Young's Elastic Modulus by first determining a constrained modulus from:

$$M_{DMT} = R_M E_D \qquad (5)$$

where R_M is an empirical value that is a function of either the horizontal stress index (K_D) defined as $(p_0 - u_0)/(\sigma'_{v0})$ or the material index (I_D) defined as $(p_1 - p_0)/(p_0 - u_0)$. Note that u_0 is the pore water pressure and σ'_{v0} is the vertical effective stress. The constrained modulus is used in the following equation, based on Poisson's ratio (ν) to determine the elastic modulus:

$$E = M_{DMT}\left[\frac{(1+\nu)(1-2\nu)}{(1-\nu)}\right] \qquad (6)$$

III. Data Reduction And Analysis

The stand-alone data acquisition program, called APMT, was developed for this research (Cosentino et al, 2006), in conjunction with incorporating digital pressure and volume equipment into the PENCEL control unit. This software uses the digital calibration data to continuously reduce the digital field data producing a stress-strain plot on the operators' computer screen throughout testing as see in Figure 4. This plot allows operators' to follow standardized testing procedures. APMT also has built-in modules that yield the critical stress-deformation information i.e., p_0, E_0, E_r and p_L. Results obtained using the APMT package were compared to hand and spreadsheet calculations. Once the output was verified this package was used to determine the four key engineering parameters obtained during PPMT testing (i.e., p_0, E_0, E_r, p_L).

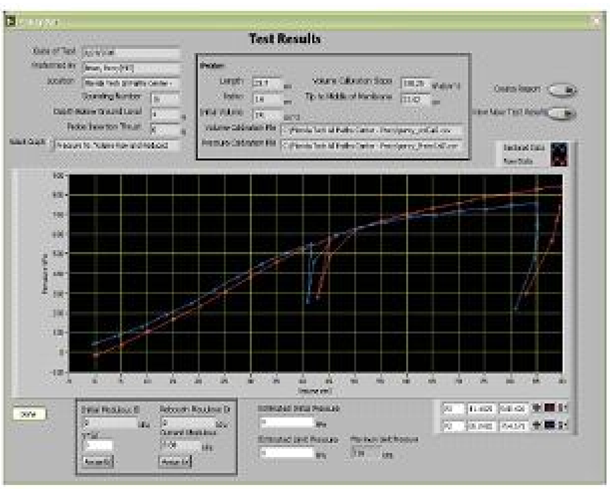

Figure 4. Data analysis performed using APMT screen (Cosentino et al 2006).

IV. Evaluation Of Correlation

A. Correlations to Engineering Parameters from PPMT

80 tests were conducted at the Cape Canaveral Site. The tests were performed in 16 soundings (i.e., a series of tests performed in one location while advancing the PENCEL probe to the desired depths), A comparison was developed using the initial and reload moduli, plus the initial or lift-off pressures and the limit pressures. Tables I to III, present the correlated results from various references relating elastic modulus, E_o, to limit pressure, p_L, and relating point resistance (q_c), to elastic modulus, E_o, and to limit pressure, p_L. Table I includes correlation relating E_o to p_L from PPMT tests in clay at the Puerto Del Rio site and published values from Ménard and Rousseau (1962). It is obvious that the average ratio for E_o/p_L is still within range of Ménard and Rousseau's published values of 6 to 16.

Table I. Comparaison Of Ppmt And Cpt Parameters (E_o/p_L)

Depth		E_o/p_L	
[m]	[ft]	PPMT	CPT Reference A
2.5	8	16	6 to 16
10.5	34.5	8	
12	39.5	8	
13.5	44.5	7	
15	50	8	
Reference A : Ménard and Rousseau (1962)			

Table II shows the average ratio for E_o/q_c based on tests results was between 3 to 20 or 4.5 to 9 for clay or fine sand, respectively (Schmertmann, 1978; Bergado and A.Khaleque, 1986).

Table II. Comparaison Of Ppmt And Cpt Parameters (E_o/Q_c)

Depth		E_o/q_c	
[m]	[ft]	PPMT	CPT References B, C
2.5	8	19.4	3 to 20
10.5	34.5	7.4	4.5 to 8.9
12	39.5	5.7	
13.5	44.5	5	
15	50	5.1	
Reference B: Schmertmann (1978) Reference C: Bergado and A. Khaleque (1986)			

Table III shows the average ratio for q_c/p_L was about 1.5 to 6 (Schmertmann, 1978). The ratios between the PPMT initial moduli and the CPT point resistances (q_c) were estimated along with ratios of the PPMT limit pressures and q_c. The E/q_c ratios are commonly used for settlements of sands (Schmertmann et al, 1978). Again, for the first two depths the comparisons are not consistent, however, for the last three

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TABLE III. COMPARAISON OF PPMT AND CPT PARAMETERS (q_c/p_L)

Depth		q_c/p_L	
[m]	[ft]	PPMT	CPT Reference B
2.5	8	1	
10.5	34.5	1.1	
12	39.5	1.5	1.5 to 6
13.5	44.5	1.5	
15	50	1.5	
Reference B: Schmertmann (1978)			

depths the values indicate that there is very consistent based on published values (Schmertmann, 1978). The correlations in Tables I to III also indicate that reliable engineering parameters can be obtained from PPMT testing.

B. Engineering Parameters from Other Devices

Correlations were performed between DMT lift-off pressures and PPMT lift-off (Figure 5) plus the DMT and PPMT initial moduli (Figure 6) from the Cape Canaveral site. Correlations between these parameters were not quite conclusive; however, ratios between the DMT and PPMT parameters were developed to provide engineers with a probable range, the DMT/PPMT elastic moduli ratios varied from 0.9 to 1.4, while the ratio of the DMT/PPMT lift-off pressures varied from 1.2 to 2.7. These ranges were based on data from PPMT tests and 20 DMT tests at 5 depths.

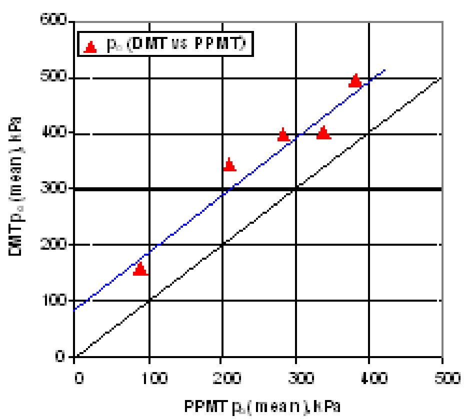

Figure 5. DMT versus PPMT Lift-off Pressures in Clay

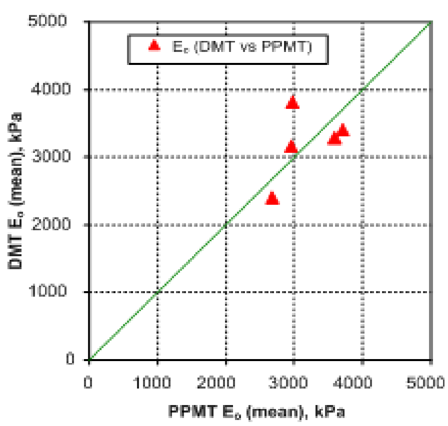

Figure 6. DMT versus PPMT Initial Moduli in Clay

C. Development of P-Y Curves

Roberston's et al (1986) PPMT-based p-y curves produce comparable Values, P_u, with Roberston's et al (1989) DMT-based p-y curves in soft clays and fine sands. The p-y curves derived from PPMT and DMT tests at this site are performed. The ultimate loads are defined as P_{u1} and P_{u2}, which are termed the lower and higher ultimate loads, respectively as seen in Figure 7. The lower ultimate load is determined at the end of the straight line portion of the p-y curve, representing the end of the elastic soil response. The higher ultimate load is defined as the intersection of the elastic-plastic response of the soil. Therefore P_{u2} is found when the extension line the elastic portion meets the plastic portion of the curve as seen in Figure 7. The maximum ultimate load is defined as P_{u1}, which correspond to the end of the elastic phase of the soil. At this point deformation of the soil is irreversible and failure results. The slope, k_s, is determined from the difference between the ultimate soil resistance, P_{u1}, and the lift-off pressure, p_o, of the elastic phase of the soil to the deflection, y_1.

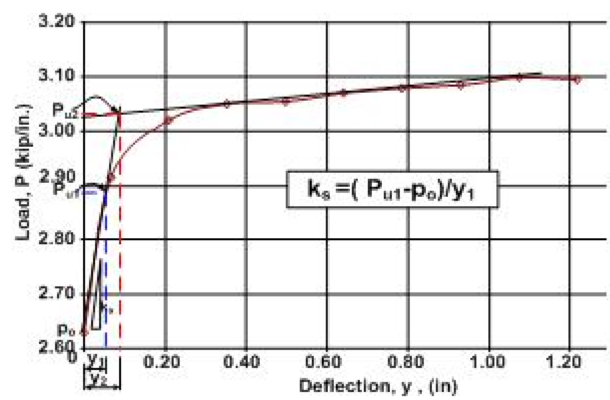

Figure 7. Depiction of Ultimate Loads and the corresponding Lateral Defections in Clays

The comparison between DMT and PPMT p-y curves was performed based on the slope of the initial portion of the curve, the ultimate soil resistance and the curve shape. The initial slopes were determined by constructing tangents through the average initial slopes for the p-y data and the average ultimate loads were determined from the p-y curves at one-inch (2.5 cm) deflection.

The values shown in table 5 for the initial slopes show several trends. First, the 10.5 m data produced higher values than the other layers due to the influence of the sandy layer at this depth. Second, the DMT slopes in the lower clay layers (12 to 15 m) are somewhat higher than the corresponding slopes from either PPMT tests. Third, the slopes have a much higher variability than the ultimate loads as evidence by the standard deviations in the table V.

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Table V. Comparaison Of Average Initial Slope And Average Ultimate Loads At One Inch (2.5 Cm) Deflection From DMT And PPMT P-Y Curves

Depth		Initial Slopes		Ultimate Loads	
		DMT	PPMT	DMT	PPMT
[m]	[ft]	[kips/in^2]		[kips/in]	
2.5	8	3.43	3.83	0.95	1
10.5	34.5	16	14	4.4	3.3
12	39.5	7.5	4.7	2.3	2.75
13.5	44.5	6.1	3.9	2.2	3
15	50	10	2.9	2.75	3.3
Avg		8.61	5.87	2.52	2.67
Std Dev		4.8	4.6	1.2	1.0

The ultimate loads for all depths were fairly similar. The data in this table was also used to determine ratios which could be evaluated to further clarify the findings. This data is shown in Table VI.

Table VI. Ratios Of PPMT And DMT P-Y Curves

Depth		Initial slopes	Ultimate loads
[m]	[ft]	DMT/PPMT	DMT/PPMT
2.5	8	0.98	0.95
10.5	34.5	1	1.33
12	39.5	1.83	0.84
13.5	44.5	1.79	0.73
15	50	2.86	0.83
Average		1.69	0.94
Std Dev		0.8	0.2

V. Summary

PPMT data produces more engineering parameters (i.e., p_0, E_0, E_r, p_L) than either DMT or CPT data. A reliable nonlinear correlation was developed between the PPMT initial elastic and the reload moduli in clays. This correlation improved when digital information along with the APMT software was used. Several correlations between PPMT data and CPT data were confirmed and shown to be very consistent. Probable ratios between PPMT and DMT parameters were presented and should be improved with further research. The pushed-in PPMT test is much faster than conventional pressuremeter testing and is recommended for use in determining the soils stress-strain response and the associated engineering parameters.

Robertson's et al (1986) PPMT based p-y curves produce comparable ultimate values, P_u, with Robertson's et al (1989) DMT based p-y curves in soft clays. A database of PPMT and DMT p-y curves should be developed for instrumented piles in various soils. Included within the data base should be methodology for conducting PPMT tests.

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